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(54) **METHOD AND APPARATUS FOR COMMUNICATION BETWEEN A PROCESSOR AND HARDWARE BLOCKS IN A PROGRAMMABLE LOGIC DEVICE**

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(51) **Int. Cl.**

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(57) **ABSTRACT**

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Method and apparatus for communication between hardware blocks configured in a programmable logic device (PLD) and a computation device external to the PLD is described. A bus controller is provided for receiving words from the computation device. Each of the words includes an address component and a data component. A first-in-first-out buffer (FIFO) is configured for communication with the bus controller to store the words. A processing engine is provided having a memory space associated with the hardware blocks and being configured to receive a word at a top of the FIFO. An address decoder is provided for decoding the address component of the word at the top of the FIFO to obtain an address of a memory location in the memory space. A strobe generator is provided for coupling a strobe signal to the processing engine. The strobe signal is configured to store the word in the memory location.

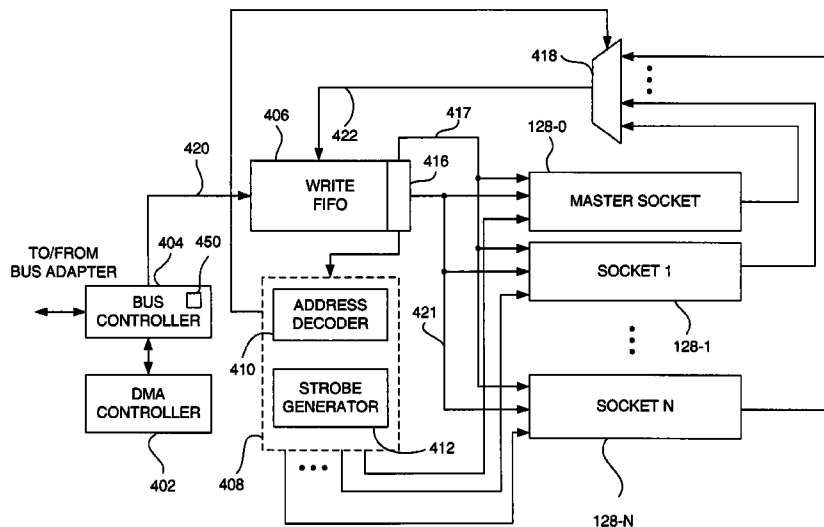
(58) **Field of Classification Search** 710/22
See application file for complete search history.

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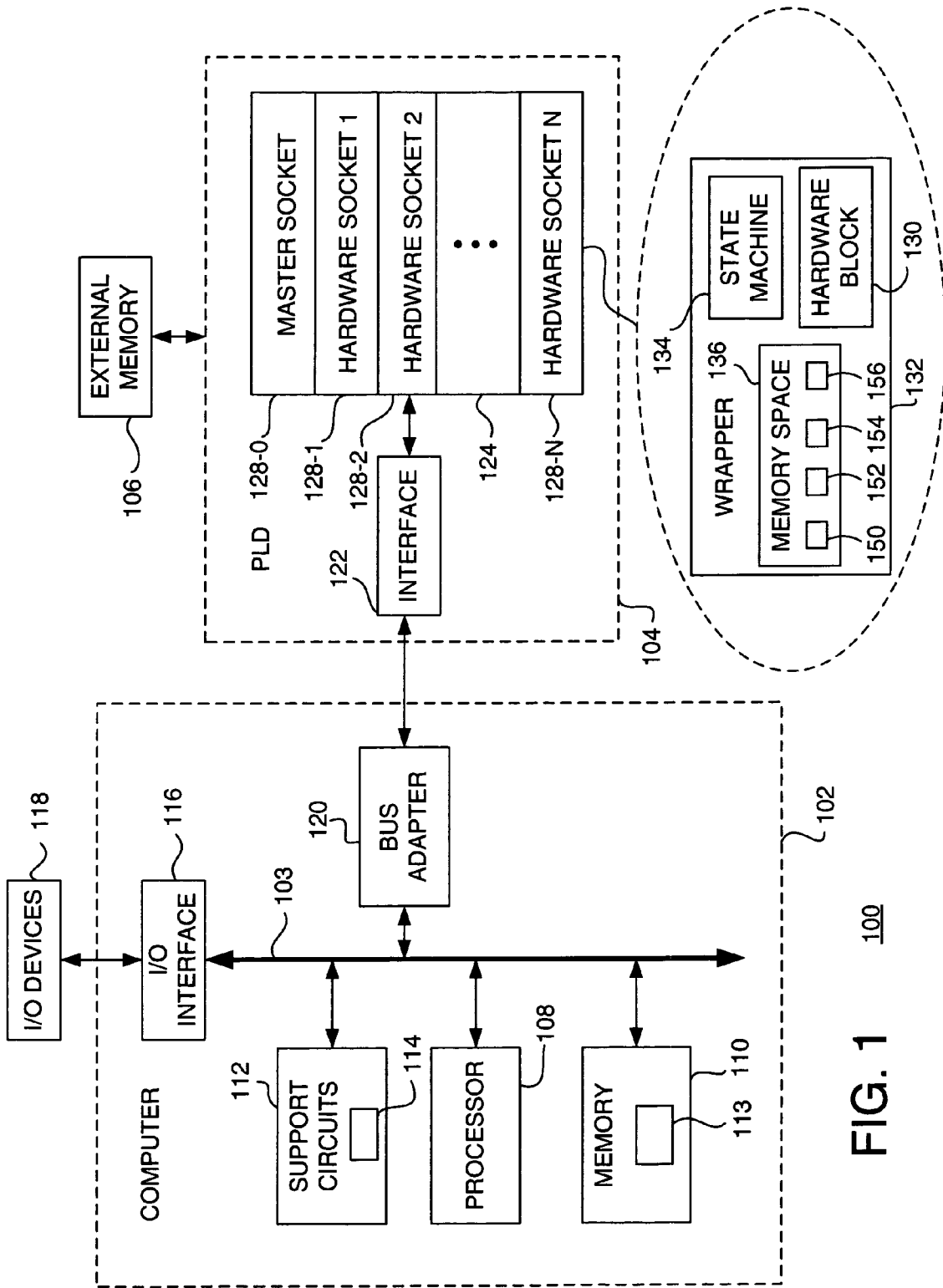


FIG. 1 100

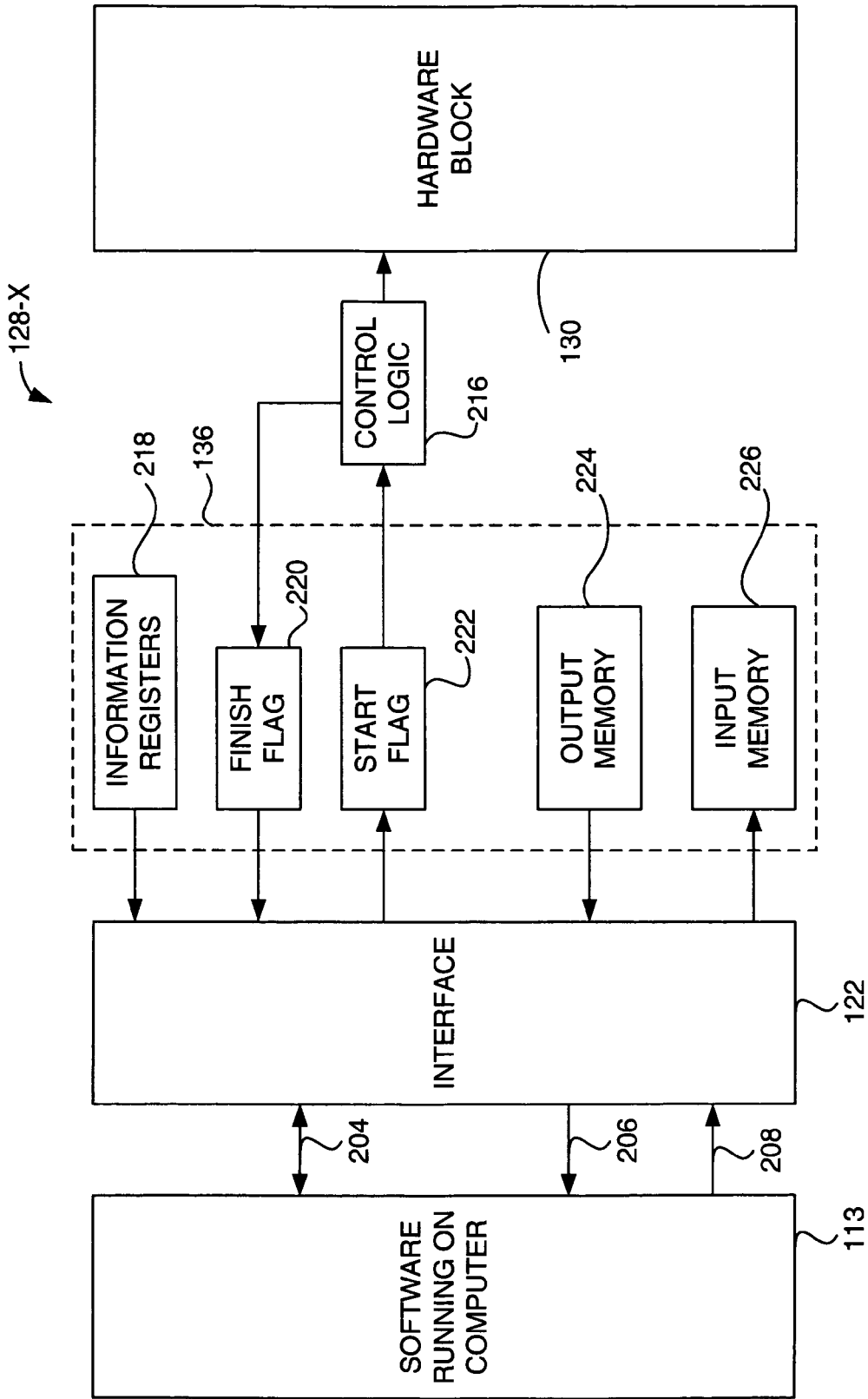


FIG. 2

ADDRESS ALLOCATION				
READ-ONLY REG FILE			WRITE-ONLY REG FILE	
SOCKET #	START	END	START	END
MASTER - 0	0	M-1	N*M	(N+1)*M-1
1	M	2*M-1	(N+1)*M	(N+2)*M-1
2	2*M	3*M-1	(N+2)*M	(N+3)*M-1
3	3*M	4*M-1	(N+3)*M	(N+4)*M-1
4	4*M	5*M-1	(N+4)*M	(N+5)*M-1
N	(N-1)*M	N*M-1	(2*N-1)*M	2*N*M-1
READ-ONLY BLOCK MEM			WRITE-ONLY BLOCK MEM	
SOCKET #	START	END	START	END
MASTER - 0	2*N*M	(2*N+1)*M-1	3*N*M	(3*N+1)*M-1
1	(2*N+1)*M	(2*N+2)*M-1	(3*N+1)*M	(3*N+2)*M-1
2	(2*N+2)*M	(2*N+3)*M-1	(3*N+2)*M	(3*N+3)*M-1
3	(2*N+3)*M	(2*N+4)*M-1	(3*N+3)*M	(3*N+4)*M-1
4	(2*N+4)*M	(2*N+5)*M-1	(3*N+4)*M	(3*N+5)*M-1
N	(3*N-1)*M	3*N*M-1	(4*N-1)*M	4*N*M-1

304

306

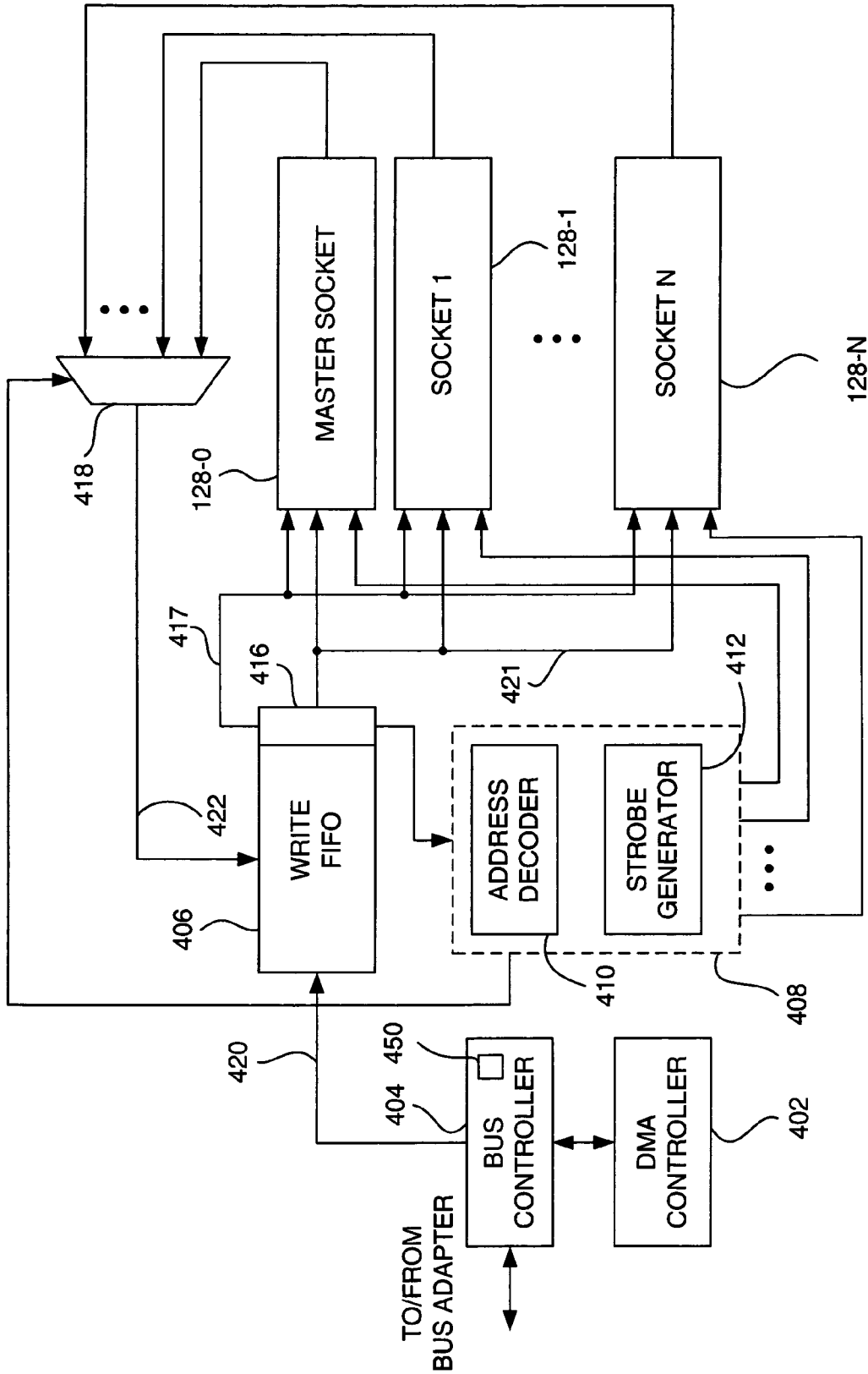
302

308

310

300

FIG. 3



400
FIG. 4

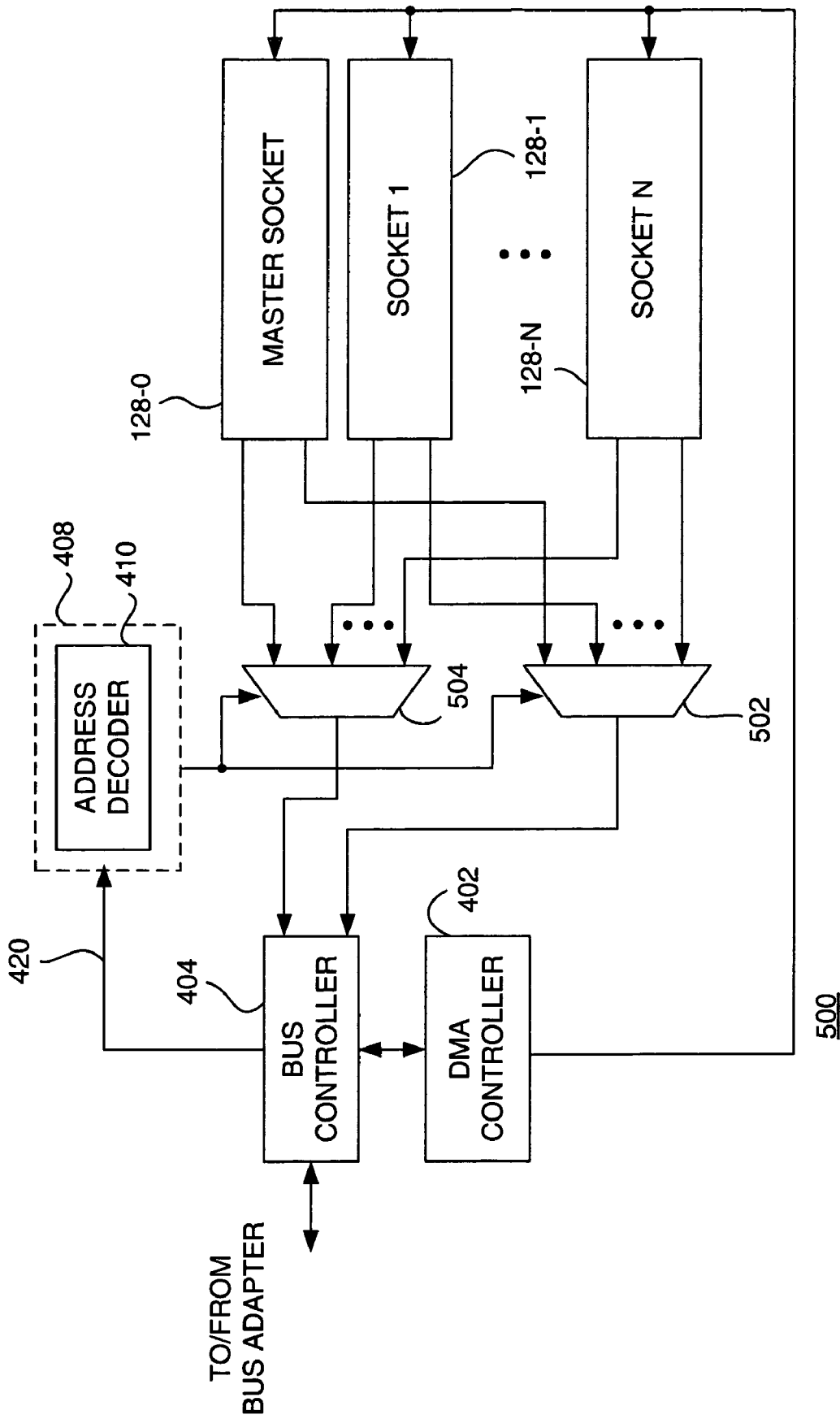


FIG. 5

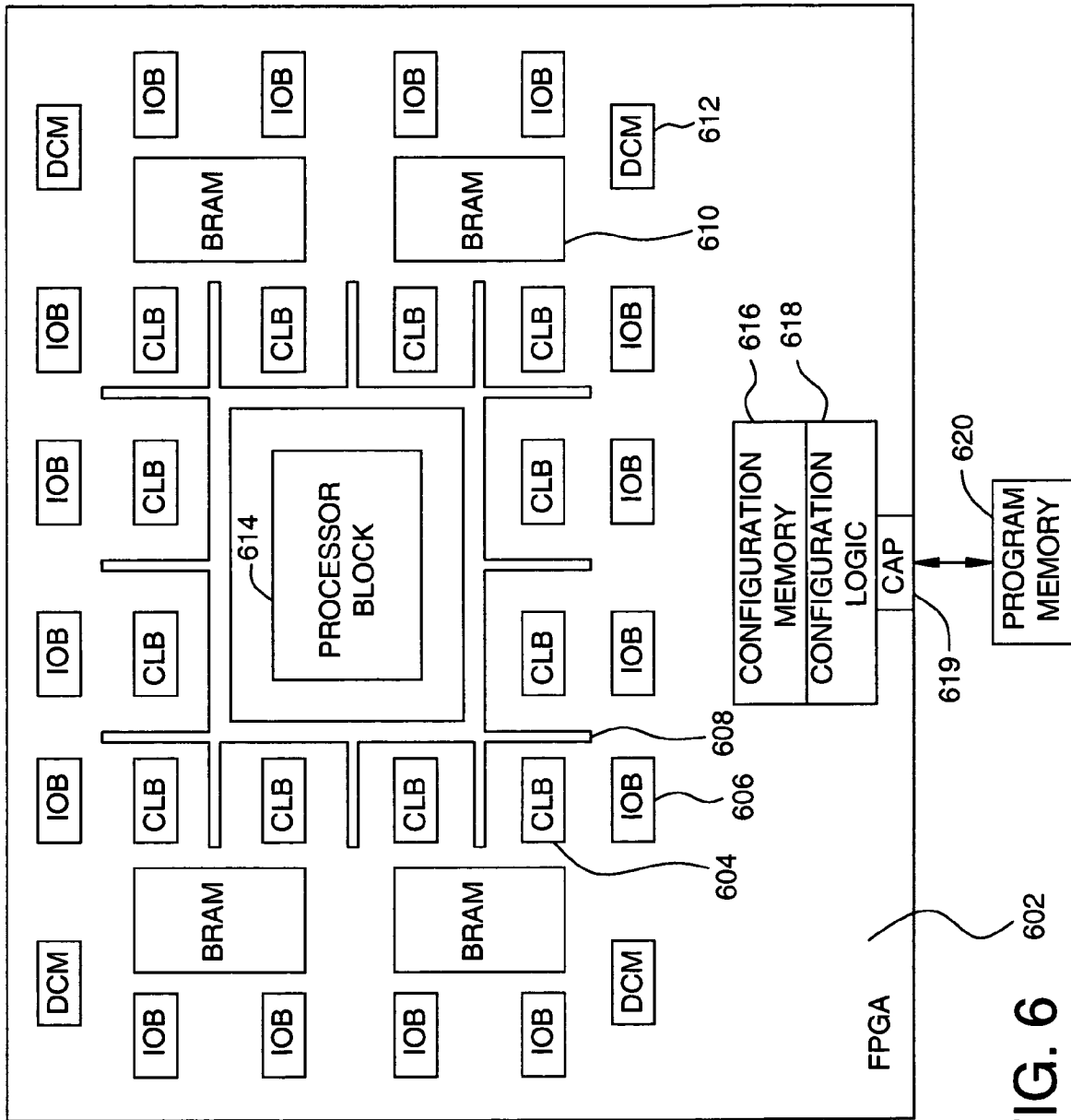


FIG. 6

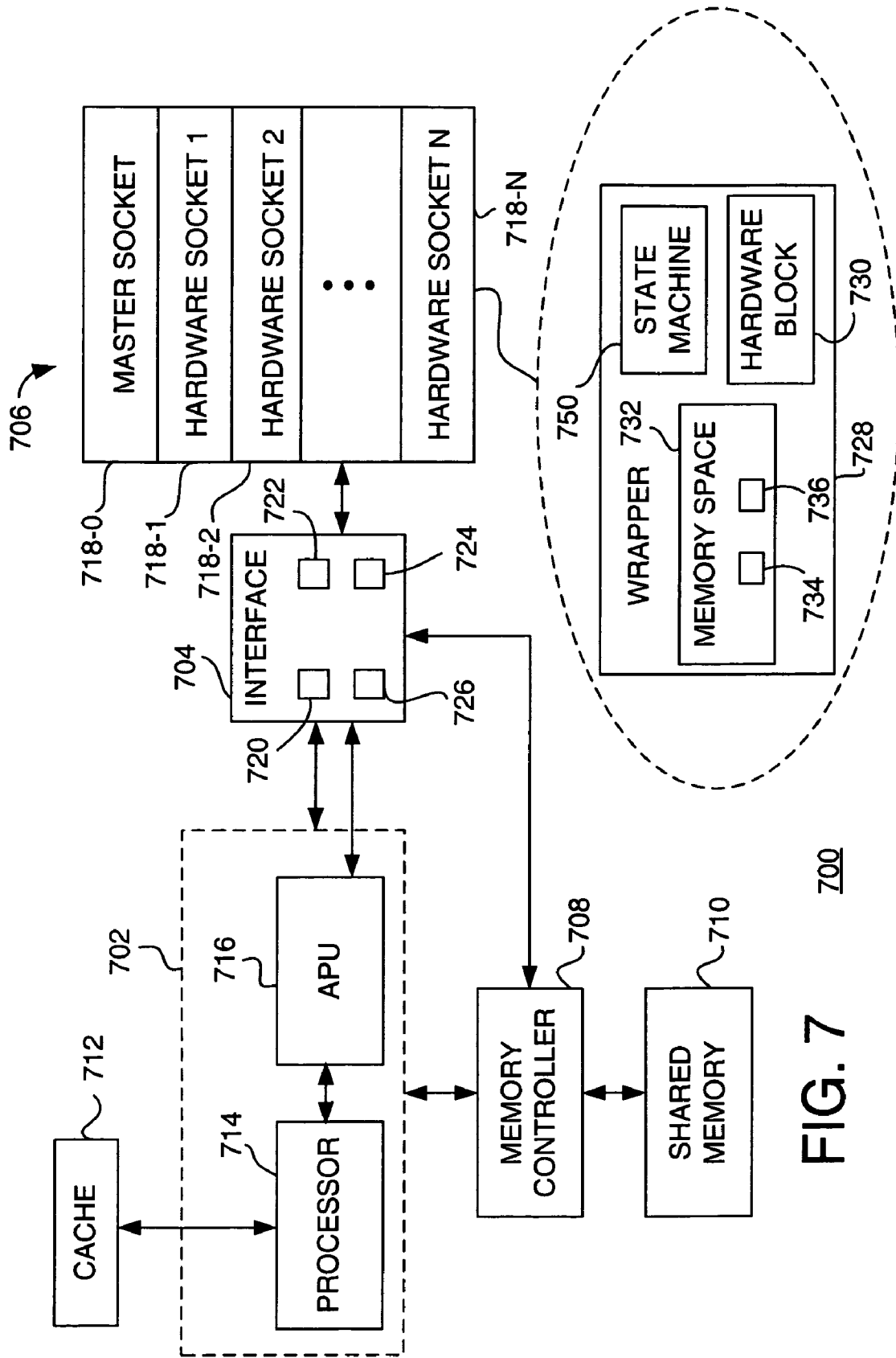


FIG. 7

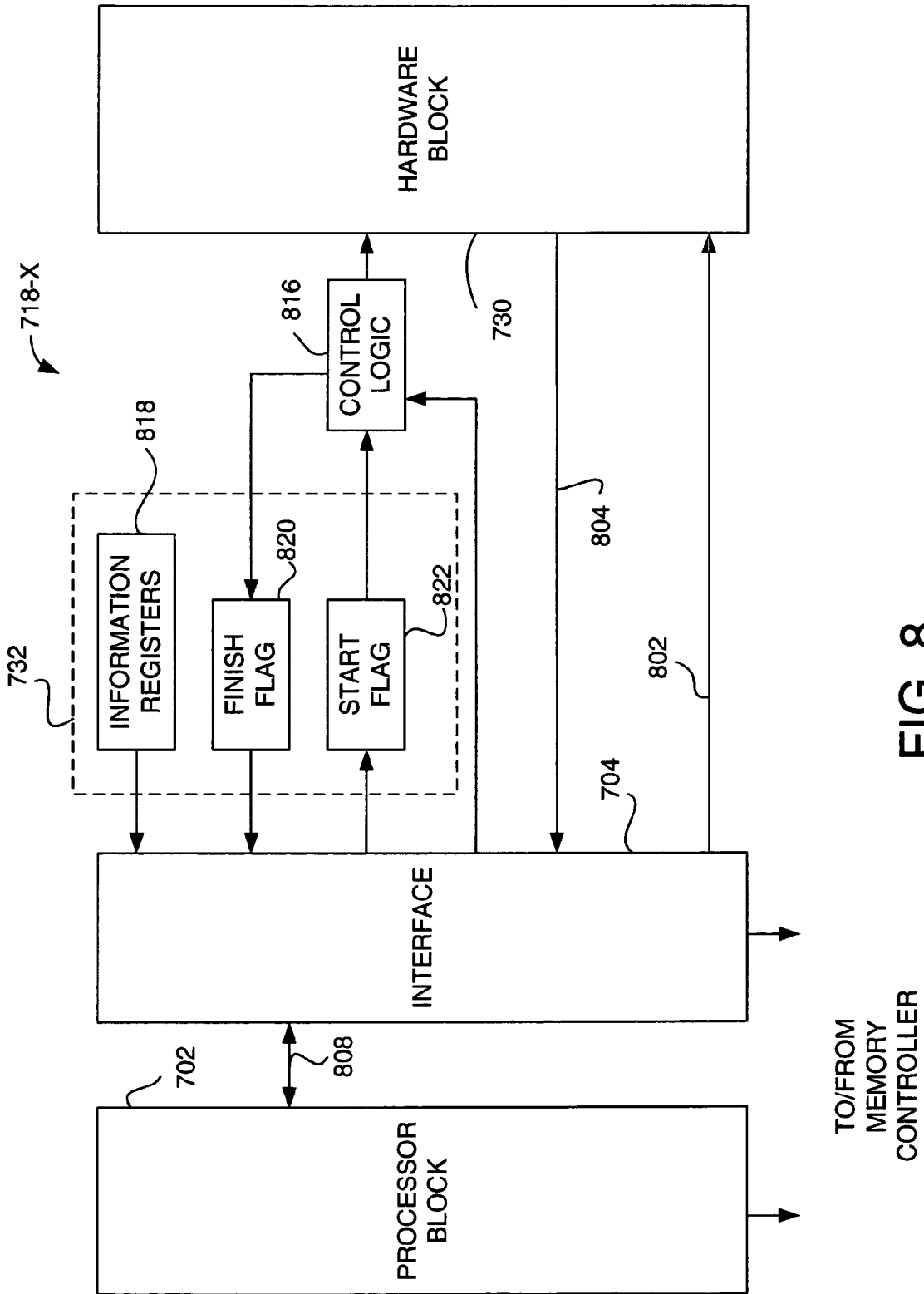
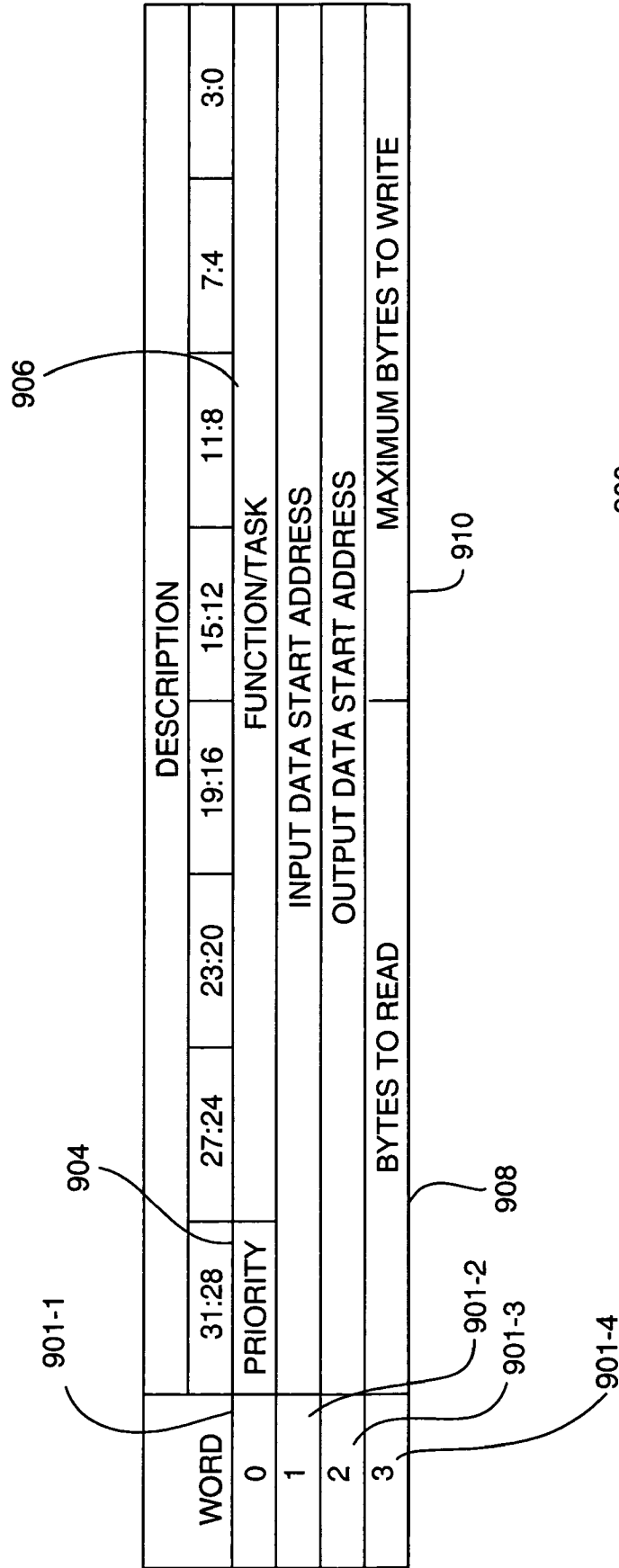


FIG. 8



900

FIG. 9

**METHOD AND APPARATUS FOR
COMMUNICATION BETWEEN A
PROCESSOR AND HARDWARE BLOCKS IN A
PROGRAMMABLE LOGIC DEVICE**

FIELD OF THE INVENTION

One or more aspects of the present invention relate generally to processing systems and, more particularly, to a method and apparatus for communication between a processor and hardware blocks in a programmable logic device.

BACKGROUND OF THE INVENTION

Traditional complex processing systems are typically implemented using software running on a microprocessor in conjunction with multiple dedicated hardware blocks. Examples of processing systems employing mixed hardware/software descriptions include various MPEG (moving picture experts group) systems for processing multimedia content, such as MPEG-4 systems. In MPEG-4, standardization efforts have resulted in a software description of the compression algorithm from which mixed hardware/software implementations can be derived. In such systems, the hardware blocks are capable of performing complex functions more efficiently than such functions could be performed using pure software.

Supporting mixed hardware/software designs of a processing system with appropriate test and emulation platforms is critical to their deployment and acceptance in the industry. The conventional approach for testing and verifying such a design involves the application of a large number of test vectors to a software simulation of the design. As design complexity increases, however, simulation times are becoming prohibitively long on current desktop computers.

Another approach for testing and verifying designs involves the use of a test engine running on a standard computation device (e.g., a computer) in communication with hardware emulators. The hardware emulators allow for more accurate and efficient simulation of the hardware portion of the design. The hardware emulators may be implemented using hardware blocks in a programmable logic device (PLD), such as a field programmable gate array (FPGA). PLDs exist as a well-known type of integrated circuit (IC) that may be programmed by a user to perform specified logic functions.

The interface between the standard computation device and the hardware emulators is becoming increasingly important as processing system designs become more complex. For video and multimedia designs that involve an enormous amount of data to be processed, communication between a test engine running on a standard computation device and hardware emulators configured in a PLD is one of the primary bottlenecks that affect the test/verification process.

Accordingly, there exists a need in the art for an improved method and apparatus for communication between a processor and hardware blocks configured in a programmable logic device.

SUMMARY OF THE INVENTION

Method and apparatus for communication between a processor and hardware blocks configured in a programmable logic device is described. One aspect of the invention relates to communication between hardware blocks configured in a programmable logic device and a computation device external to the programmable logic device. A bus controller is

provided for receiving words from, and transmitting words to, the computation device. At least one first-in-first-out buffer (FIFO) is provided for communication with the bus controller to store the words. A Processing engine is provided having a memory space associated with the hardware blocks. The processing engine is configured to receive the words in the FIFO(s). An address decoder is provided for decoding an address component of the words in the FIFO(s) to obtain addresses of memory locations in the memory space. A strobe generator is provided for coupling a strobe signal to the processing engine. The strobe signal is configured to store the words in the respective memory locations.

In another embodiment, communication between hardware blocks and a processor in a programmable logic device is described. A shared memory is provided along with a memory controller for controlling access to the shared memory. An interface is configured to receive auxiliary instructions from the processor, select the hardware blocks for the requested tasks in response to the auxiliary instructions, notify the hardware blocks of those tasks, and arbitrate access to the memory controller among the hardware blocks.

BRIEF DESCRIPTION OF THE DRAWINGS

Accompanying drawing(s) show exemplary embodiment(s) in accordance with one or more aspects of the invention; however, the accompanying drawing(s) should not be taken to limit the invention to the embodiments(s) shown, but are for explanation and understanding only.

FIG. 1 is a block diagram depicting an exemplary embodiment of a processing system constructed in accordance with one or more aspects of the invention;

FIG. 2 is a functional block diagram depicting an exemplary embodiment an interface between software running on a processor and a hardware block of the processing system in FIG. 1;

FIG. 3 is a table depicting an exemplary address allocation scheme in accordance with one or more aspects of the invention;

FIGS. 4 and 5 are block diagrams depicting an exemplary embodiment of a interface between a processor and multiple hardware blocks in accordance with one or more aspects of the invention;

FIG. 6 is a block diagram depicting an exemplary embodiment of an FPGA coupled to a program memory;

FIG. 7 is a block diagram depicting another exemplary embodiment of a processing system constructed in accordance with one or more aspects of the invention;

FIG. 8 is a functional block diagram depicting an exemplary embodiment an interface between software running on a processor and a hardware block of the processing system in FIG. 7; and

FIG. 9 is a table depicting an exemplary embodiment of an auxiliary instruction in accordance with one or more aspects of the invention.

DETAILED DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram depicting an exemplary embodiment of a processing system **100** constructed in accordance with one or more aspects of the invention. The system **100** includes a computer **102** in communication with a programmable logic device (PLD) **104**. The PLD **104** may be in communication with external memory **106**. In general, the computer **102** is configured to execute software code that makes use of one or more hardware blocks configured in the PLD **104**. The hardware blocks may act as "hardware accel-

erators” configured to perform particular functions more efficiently than software implementations of such functions. In addition, the hardware blocks may act as “hardware emulators” for more realistic and efficient testing and verification of a design.

In particular, the computer 102 includes a processor 108, memory 110, support circuits 112, an input/output (I/O) interface 116, and a bus adapter 120, each of which is in communication with a system bus 103. The processor 108 may be any type of microprocessor known in the art. The support circuits 112 for the processor 108 include conventional cache, power supplies, clock circuits, data registers, I/O interfaces, and the like, as well as a bus arbiter 114. The bus arbiter 114 determines which circuit in the computer 102 has control of the system bus 103. The system bus 103 may comprise any type of bus known in the art, such as a typical local bus found in many personal computers known in the art.

The I/O interface 116 may be in communication with various I/O devices 118, such as a conventional keyboard, mouse, printer, display, and the like. The bus adapter 120 is configured to couple the PLD 104 to the system bus 103. The bus adapter 120 acts as a bridge between buses and allows transfers to take place between the PLD 104 and other devices coupled to the system bus 103, such as the processor 108 and the memory 110. For example, the bus adapter 120 may comprise a local bus to peripheral component interface (PCI) bus bridge or like type bus adapter known in the art. Alternatively, the PLD 104 could support a number of other bus formats known in the art (e.g., the PLD 104 may be configured with USB, FireWire, or other bus formats). The memory 110 stores software 113 to be executed by the processor 108.

The PLD 104 is configured with an interface 122 in communication with a processing engine 124. The processing engine 124 includes sockets 128-0 through 128-N (collectively referred to as sockets 128), where N is an integer. The sockets 128 include a master socket 128-0 and N hardware sockets 128-1 through 128-N. The sockets 128-1 through 128-N may include various hardware blocks. The master socket 128-0 may be used to identify the presence of hardware blocks in the sockets 128-1 through 128-N and to control transfers between the PLD 104 and the external memory 106. The PLD 104 may comprise a field programmable gate array (FPGA) or like type device known in the art. An exemplary FPGA is shown in FIG. 6.

The interface 122 is configured to provide access to the sockets 128 for use by the computer 102. In general, the interface 122 controls the transfer of data, address, and control information between the processing engine 124 and the system bus 103. The software 113 running on the processor 108 may access the sockets 128 through the interface 122. An exemplary embodiment of a flow control mechanism implemented by the interface 122 is described below with respect to FIGS. 4 and 5.

Each of the sockets 128 comprises a hardware block 130 and a wrapper 132. The wrapper 132 provides a standard interface to the hardware block 130. That is, each of the sockets 128 includes a standard interface to its respective hardware block. The wrapper 132 includes a data transfer state machine 134 and a memory space 136. The data transfer state machine 134 is configured to communicate with the interface 122 and to control data flow to and from the hardware block 130. The memory space 136 includes a write-only register file 150, a read-only register file 152, a write-only block memory 154, and read-only block memory 156. The terms “write” and “read” are defined with respect to the interface 122. That is, the interface 122 stores data to the write-only memories 150 and 154 and reads data from the

read-only memories 152 and 156. Conversely, the hardware block 130 reads data from the write-only memories 150 and 154 and writes data to the read-only memories 152 and 156.

The register file memories 150 and 152 are used for writing and reading control signals. The write-only register file 150 is used to store flags and parameters that are required by the hardware block 130 (e.g., a status flag indicating the presence of input data). The read-only register file 152 is used to convey various flags and parameters computed by the hardware block 130 (e.g., a status flag indicating the presence of completed output data). The read-only register file 152 can also contain any information that the hardware block 130 would like to transmit to the computation device (e.g., functional capabilities, estimated performance of specified tasks, etc.). The block memories 154 and 156 are used for transferring data between the interface 122 and the hardware block 130. For example, the hardware block 130 may be a discrete cosine transform (DCT) circuit for performing DCT operations. Input data comprising blocks of pixel values are received through the interface 122 and stored in the write-only block memory 154. Output data comprising blocks of DCT coefficients are stored in the read-only block memory 156 and read-out through the interface 122. An exemplary configuration for the memory space 136 of a socket is described immediately below with respect to FIG. 2.

FIG. 2 is a functional block diagram depicting an exemplary embodiment an interface between the software 113 running on the processor 108 and a socket 128-X of the sockets 128 in the processing engine 124. The memory space 136 includes one or more information registers 218, a finish flag register 220, a start flag register 222, output memory 224, and input memory 226. The wrapper 132 for the socket 128-X includes control logic 216. The information registers 218 and the finish flag 220 form the read-only register file space, and the start flag 222 forms the write-only register file space. The output memory 224 forms the read-only block memory space, and the input memory 214 forms the write-only block memory space.

Data is written to the input memory 226 by the software 113 via path 208 to the interface 122. The hardware block 130 is configured to read the input data from the input memory 226 for processing. The hardware block 130 is configured to store output data to the output memory 224. The output data is read by the software 113 via path 206 from the interface 122. Various protocols may be used to perform the data transfer to the input memory 226 (e.g., streaming data based on empty/full flags of the input memory 226). One method is the use of a start flag register 222. The software 113 sets the start flag register 222 via control path 204 to the interface 122. The control logic 216 detects the state of the start flag register 222 and signals the hardware block 130 to begin processing input data in the input memory 226.

The hardware block 130 signals the control logic 216 after processing is complete and output data is stored in the output memory 224. In response, the control logic 216 sets the finish flag register 220. Various protocols may be used to perform the data transfer from the output memory 224 (e.g., streaming data based on empty/full flags of the output memory 224, interrupt signals sent from the interface 122 to the processor 108). One method is the use of a finish flag register 220 that is polled by the software 113 running on microprocessor 108. The software 113 periodically polls the state of the finish flag register 220 and reads data from the output memory 224 in response to the finish flag register 220 being set. The information registers 218 may be used to store data indicative of the capabilities of the hardware block 130. For example, the information registers 218 may be configured to store a list of

task(s) that the hardware block **130** is capable of performing, as well as a cost function related to how fast the hardware block **130** can perform the task(s).

FIG. **3** is a table **300** depicting an exemplary address allocation scheme that may be employed with respect to the memory space **136** for each of the sockets **128**. In the present example, there are N sockets **128** and M address locations in each of the memory spaces **150** through **156** for each of the sockets **128** where M is an integer. The software **113** may access the memories in the sockets **128** in accordance with the addresses in the table **300** (i.e., the write-only register file **150**, the read-only register file **152**, the write-only block memory **154**, and the read-only block memory **156**).

In particular, a column **302** in the table **300** indicates the socket number ranging from zero (the master socket **128-0**) through N (the socket **128-n**). A portion **304** of the table **300** indicates an exemplary address allocation for the read-only register file **152** in each of the sockets **128**. In the present example, the read-only register file **152** for the master socket **128-0** starts at address **0** and ends at address $M-1$. The read-only register file **152** for the socket **128-1** starts at address M and ends at address $2M-1$, and so on until the read only register file **152** for the socket **128-N** starts at address $(N-1)M$ and ends at address $NM-1$.

A portion **306** of the table **300** indicates an exemplary address allocation for the write-only register file **150** in each of the sockets **128**. The write-only register file **150** for the master socket **128-0** begins at address NM and ends at address $(N+1)M-1$, and so on until the write-only register file **150** for the socket **128-N** begins at address $(2N-1)M$ and ends at address $2NM-1$. A portion **308** of the table **300** indicates an exemplary address allocation for the read-only block memory **156** in each of the sockets **128**. The read-only block memory **156** for the master socket **128-0** begins at address $2NM$ and ends at address $(2N+1)M-1$, and so on until the read-only block memory **156** for the socket **128-N** begins at address $(3N-1)M$ and ends at address $3NM-1$. Finally, a portion **310** of the table **300** indicates an exemplary address allocation for the write-only block memory **154** in each of the sockets **128**. The write-only block memory **154** for the master socket **128-0** begins at address $3NM$ and ends at address $(3N+1)M-1$, and so on until the write-only block memory **154** for the socket **128-N** begins at address $(4N-1)M$ and ends at address $4NM-1$.

Returning to FIG. **1**, in one embodiment, the read-only register file **152** of the master socket **128-0** is configured to store a hardware identification value. The hardware identification value provides information related to which of the sockets **128** in the processing engine **124** includes a hardware block. In one embodiment, the hardware identification value comprises an $N+1$ bit word, where each bit indicates the presence (e.g., a "1" value) or the absence (e.g., a "0" value) of a hardware block in a respective one of the sockets **128**. That is, the least significant bit is associated with the master socket **128-0** and the most significant bit is associated with the socket **128-N**. For example, the hardware identification value "00000 . . . 00001000011" indicates that the master socket **128-0** and sockets **128-1** and **128-6** include hardware blocks.

The software **113** may access the read-only register file **152** in the master socket **128-0** to read the hardware identification value and determine which of the sockets **128** may be used for processing. In one embodiment, functionality of the available sockets is determined using a predefined table of socket numbers and their corresponding hardware functionality. In another embodiment, the read-only register file **152** in the master socket **128-0** is configured to store information related to the functionality of the hardware block in each of the

available sockets. As the PLD **104** is programmable and partial reconfiguration of PLD **104** is possible, individual hardware blocks in the sockets **128** may change dynamically over time, thus modifying the value of read-only register file **152**. The polling of the register file **152** can be performed by either the software **113** or by the interface **122** and future tasks allocated accordingly.

FIGS. **4** and **5** are block diagrams depicting an exemplary embodiment of the interface **122** coupled to the sockets **128** in accordance with one or more aspects of the invention. In particular, FIG. **4** depicts a portion **400** of the interface **122** related to writing data to the sockets **128**. FIG. **5** depicts a portion **500** of the interface **122** related to reading data from the sockets **128**. Identical elements in FIGS. **4** and **5** are designated with identical reference numerals. For purposes of clarity, elements specific to reading data from the sockets **128** are omitted from FIG. **4**. Likewise, elements specific to writing data to the sockets **128** are omitted from FIG. **5**.

The interface **122** employs a flow control mechanism to control writing to, and reading from, the memory space of the sockets **128**. Referring to FIGS. **1**, **4**, and **5**, the interface **122** includes a bus controller **404** and a direct memory access (DMA) controller **402**. The bus controller **404** is configured for communication with the bus adapter **120**. A port of the bus controller **404** is in communication with a port of the DMA controller **402**.

The DMA controller **402** includes internal registers (not shown) that control its operation. The internal registers typically include an address register, a byte count register, and a control register, such registers being well known in the art. For a data transfer from the bus adapter to the interface **122**, the address register is loaded with the desired memory address in which to store the data. The memory address is defined with respect to the combined memory space of the sockets **128** (e.g., the example shown in FIG. **3**). The byte count register is loaded with the number of bytes to be transferred, and the control register is loaded with control data (e.g., data indicative of the direction of the transfer). The internal registers may be loaded with their respective data by the processor **108**. Such initialization of the DMA controller **402** is well known in the art.

After the internal registers are initialized, the DMA controller **402** signals the bus controller **404** that it should request control of the system bus **103**. The bus controller **404** is configured for bus mastering such that the interface **122** is capable of becoming a master of the system bus **103**. The bus controller **404** negotiates with the bus arbiter **114** for control of the system bus **103**. Once the bus controller **404** has control of the system bus **103**, the DMA controller **402** then controls the DMA transfer between the memory **110** and the interface **122**. When the DMA transfer is complete, the DMA controller **402** notifies the bus controller **404** that it no longer requires control of the system bus **103**. The bus controller **404** then relinquishes control of the system bus **103** to the bus arbiter **114**. By employing the PLD **104** as a bus master, this embodiment of the invention reduces overhead with respect to communication between the PLD **104** and the computer **102**.

Referring specifically to FIG. **4**, the interface **122** further includes write first-in-first-out circuitry (write FIFO) **406**, control logic **408**, and a multiplexer **418**. An output port of the bus controller **404** is coupled to a data input port **420** of the write FIFO **406**. A data output port **421** of the write FIFO **406** is coupled to an input port of each of the sockets **128**. In one embodiment, the write FIFO **406** includes a single FIFO for the entire interface **122**. In another embodiment, the write FIFO **406** includes a separate FIFO for each of the sockets **128**. In such an embodiment, the bus controller **404** includes

de-multiplexing logic **450** for selecting a FIFO for loading data therein. Use of a FIFO for each of the sockets **128** allows the hardware blocks in the sockets **128** to accept data at their own desired rates, which can be different for each of the hardware blocks.

The write FIFO **406** comprises multiple memory locations, which include a top memory location ("top **416**"). The control logic **408** is in communication with the write FIFO **406** to read data at the top **416**. The control logic **408** includes an address decoder **410** and a strobe generator **412**. The control logic **408** includes N+1 output ports respectively coupled to input ports of the sockets **128-0** through **128-N**. Each of the sockets **128** is in communication with the write FIFO **406** via a path **417** to read data at the top **416**. The multiplexer **418** includes N+1 input ports respectively coupled to output ports of the sockets **128-0** through **128-N**. An output port of the multiplexer **418** is coupled to a pop control terminal **422** of the write FIFO **406**.

In operation, information to be processed by the sockets **128** is transferred from the computer **102** (e.g., from the memory **110**) to the write FIFO **406** using the DMA/bus mastering process described above. In particular, the bus controller **404** pushes each received word into the write FIFO **406** via the data input port **420**. Each received word includes one or more of an address component, a control component, and a data component.

The address decoder **410** reads the address component of the word at the top **416** of the write FIFO **406** and decodes the address. That is, the address decoder **410** determines which memory location in the combined memory space of the sockets **128** is being addressed. The strobe generator **412** then provides a strobe signal to the addressed memory location in the address one of the sockets **128**. For example, in accordance with the exemplary allocation scheme of FIG. 3, an address of $(3N+3)M$ refers to the write-only block memory **154** of the socket **128-3**. After decoding the address $(3N+3)M$, the strobe generator **412** would generate a strobe signal for the write-only block memory **154** of the socket **128-3**.

Each of the sockets **128** may read a write valid flag from the word at the top **416** of the write FIFO **406** via the path **417**. The write valid flag comprises at least a portion of the control component of the word at the top **416** of the write FIFO **406**. For each of the sockets **128**, the write valid flag indicates that the word at its input is valid. If valid, the word at the top **416** of the write FIFO **406** is stored in the addressed memory location in the address one of the sockets **128** in accordance with the strobe signal generated by the strobe generator **412**. After the word is stored, the addressed one of the sockets **128** asserts a write ready signal to the multiplexer **418**. The multiplexer **418** selects the write read signal of the addressed one of the sockets **128**, which pops the write FIFO **406** and cause the next word to be located at the top **416** of the write FIFO **406**. The process is then repeated. In this manner, information may be transferred from the computer **102** to one or more of the sockets **128**. The selection control for the multiplexer **418** is performed by the address decoder **410**. In one embodiment, data is written to the same socket as long as the write FIFO **406** is not empty.

Referring specifically to FIG. 5, the interface **122** further includes a multiplexer **502** and a multiplexer **504**. An output port of the bus controller **404** is coupled to the control logic **408**. An output port of the control logic **408** is coupled to a control terminal of each of the multiplexers **502** and **504**. Output ports of the multiplexers **502** and **504** are coupled to input ports of the bus controller **404**. Input ports of the multiplexer **504** are coupled to data output ports of the sockets **128**. Input ports of the multiplexer **502** are coupled to strobe

output ports of the sockets **128**. An output port of the DMA controller **402** is coupled to an input port of each of the sockets **128**.

In operation, information produced by the sockets **128** is transferred from the PLD **104** to the computer **102** using the DMA/bus mastering process described above. In particular, the bus controller **404** receives a read request from the computer **102**. The address decoder **410** decodes an address component of the read request to determine which memory location in the combined memory space of the sockets **128** is being addressed. The control logic **408** provide a control signal to the multiplexers **502** and **504** to select a socket of the sockets **128** in accordance with the address decoded by the address decoder **410**. For example, in accordance with the exemplary allocation scheme of FIG. 3, an address of $(2N+3)M$ refers to the read-only block memory **152** of the socket **128-3**. After decoding the address $(2N+3)M$, the control logic **408** causes the multiplexer **504** to select the data output port of the socket **128-3**, and the multiplexer **502** to select the strobe output port of the socket **128-3**.

In response to the read request, the bus controller **404** becomes the master of the system bus **103**, as described above. The bus controller **404** notifies the DMA controller **402** that it has control of the system bus **103**, and the DMA controller **402** notifies the sockets **128** to begin transferring data to a specified address in the memory **110**. As described above, the internal registers **403** of the DMA controller **402** are initialized with address and control information for the transfer. The addressed one of the sockets **128** provides the data to the bus controller **404** through the multiplexer **504**, and provides the strobe signal for the memory **110** to the bus controller **404** through the multiplexer **502**. The information is then coupled to the system bus **103** such that the data is stored in the memory **110**. The process is then repeated for each read request. In this manner, information may be transferred from the PLD **104** to the computer **102**.

FIG. 6 is a block diagram depicting an exemplary embodiment of an FPGA **602** coupled to a program memory **620**. The FPGA **602** may be used as the PLD **104** in the system **100** of FIG. 1. The FPGA **602** illustratively comprises programmable logic circuits or "blocks", illustratively shown as CLBs **604**, IOBs **606**, and programmable interconnect **608** (also referred to as "programmable logic"), as well as configuration memory **616** for determining the functionality of the FPGA **602**. The FPGA **602** may also include an embedded processor block **614**, as well as various dedicated internal logic circuits, illustratively shown as blocks of random access memory ("BRAM **610**"), configuration logic **618**, and digital clock management (DCM) blocks **612**. Those skilled in the art will appreciate that the FPGA **602** may include other types of logic blocks and circuits in addition to those described herein.

As is well known in the art, the IOBs **606**, the CLBs **604**, and the programmable interconnect **608** may be configured to perform a variety of functions. Notably, the CLBs **604** are programmably connectable to each other, and to the IOBs **606**, via the programmable interconnect **608**. Each of the CLBs **604** may include one or more "slices" and programmable interconnect circuitry (not shown). Each CLB slice in turn includes various circuits, such as flip-flops, function generators (e.g., a look-up tables (LUTs)), logic gates, memory, and like type well-known circuits. The IOBs **606** are configured to provide input to, and receive output from, the CLBs **604**.

Configuration information for the CLBs **604**, the IOBs **606**, and the programmable interconnect **608** is stored in the configuration memory **616**. The configuration memory **616** may include static random access memory (SRAM) cells.

The configuration logic **618** provides an interface to, and controls configuration of, the configuration memory **616**. A configuration bitstream produced from the program memory **620** may be coupled to the configuration logic **618** through a configuration port **619**. The configuration process of FPGA **602** is also well known in the art.

The DCM blocks **612** provide well-known clock management circuits for managing clock signals within the FPGA **602**, such as delay lock loop (DLL) circuits and multiply/divide/de-skew clock circuits. The processor block **614** comprises a microprocessor core, as well as associated control logic. Notably, such a microprocessor core may include embedded hardware or embedded firmware or a combination thereof for a “hard” or “soft” microprocessor. A soft microprocessor may be implemented using the programmable logic of the FPGA **602** (e.g., CLBs **604**, IOBs **606**). For example, a MICROBLAZE soft microprocessor, available from Xilinx of San Jose, Calif., may be employed. A hard microprocessor may be implemented using an IBM POWER PC, Intel PENTIUM, AMD ATHLON, or like type processor core known in the art.

The processor block **614** is coupled to the programmable logic of the FPGA **602** in a well-known manner. For purposes of clarity by example, the FPGA **602** is illustrated with 12 CLBs, 16 IOBs, 4 BRAMs, 4 DCMs, and one processor block. Those skilled in the art will appreciate that actual FPGAs may include one or more of such components in any number of different ratios. For example, the FPGA **602** may be selected from the VIRTEX-4 family of products, commercially available from Xilinx, Inc. of San Jose, Calif.

FIG. **7** is a block diagram depicting another exemplary embodiment of a processing system **700** constructed in accordance with one or more aspects of the invention. The system **700** may be implemented entirely within a PLD, such as the FPGA **602** of FIG. **6** or the Virtex-4 FPGA available from Xilinx, Inc. of San Jose, Calif. The system **700** comprises a processor block **702**, an interface **704**, a processing engine **706**, a memory controller **708**, shared memory **710**, and cache memory **712**. In one embodiment, the processor block **702** includes a processor **714** and an auxiliary processor unit (APU) **716** (an example of an APU is found in the Virtex-4 FPGA, further details are in co-pending application, U.S. application Ser. No. 10/912,844, entitled “Coprocesor Interface Controller”, by Ahmad R. Ansari, et. al., filed Aug. 6, 2004, which is herein incorporated by reference). The processing engine **706** includes sockets **718-0** through **718-N** (collectively referred to as sockets **718**), where N is an integer. Similar to the embodiment of FIG. **1**, the sockets **718** include a master socket **718-0** and N hardware sockets **718-1** through **718-N**. In contrast to the embodiment of FIG. **1**, the processor **714** and APU **716** are embedded in the PLD, rather than being part of an external computation device. The memory **710** can be either embedded in the PLD or be external to the PLD.

A port of the processor **714** is coupled to a port of the APU **716**. Another port of the processor **714** is coupled to a port of the cache memory **712**. A port of the processor block **702** is coupled to a port of the memory controller **708**. Another port of the APU **716** is coupled to a port of the interface **704**. Another port of the interface **704** is coupled to another port of the memory controller **708**. Yet another port of the interface **704** is coupled to the processing engine **706**. Another port of the memory controller **708** is coupled to a port of the shared memory **710**.

In operation, the processor **714** executes software code that makes use of one or more hardware blocks of the processing engine **706**. The processor **714** may be any type of microprocessor known in the art. The processor **714** may use the cache

memory **712** for storing software instructions and/or local data. In some cases, the software instructions stored in the cache **712** may be fetched from another memory, such as the shared memory **710**. The processor **714** may access the shared memory **710** via the memory controller **708**. The memory controller **708** is configured to arbitrate access to the shared memory **710** among the processor block **702** and the interface **704**.

Some of the software instructions comprise auxiliary instructions that are not executed by the processor **714**, but are rather sent by the processor **714** to the APU **716**. Notably, an auxiliary instruction may comprise a task to be performed by a socket of the sockets **718** in the processing engine **706**. Upon receiving an auxiliary instruction associated with the processing engine **706**, the APU **716** forwards the auxiliary instruction to the interface **704**. The data to be processed by the processing engine **706** is stored in the shared memory **710**.

The interface **704** includes decoder logic **720** for decoding auxiliary instructions received from the APU **716**. Notably, FIG. **9** is a table depicting an exemplary embodiment of an auxiliary instruction **900** in accordance with one or more aspects of the invention. The auxiliary instruction **900** comprises four words **901-1** through **901-4** (collectively referred to as words **901**). For purposes of clarity by example, each of the words **901** includes 32 bits. It is to be understood that the words may comprise any number of bits.

The word **901-1** includes a priority component **904** and a function/task component **906**. The function/task component **906** includes data representative of the particular task to be performed by the processing engine **706**. The priority component **904** includes data representative of the priority of the task with respect to a predefined priority scale. The priority component **904** may be used to aid the interface **704** in selecting a socket for performing the task among multiple contending sockets. In the present example, the priority component **904** includes four bits for 16 possible priority levels, and the function/task component **906** includes 28 bits. It is to be understood that the priority component **904** and the function/task component **906** may have other bit-sizes.

The word **901-2** includes data representative of the start address in the shared memory **710** for the input data to be processed by the processing engine **706**. The word **901-2** includes data representative of the start address in the shared memory **710** for the output data produced by the processing engine **706** in response to processing the input data. The word **901-4** includes a first component **908** and a second component **910**. The first component **908** includes data representative of the number of bytes to be read by the processing engine **706** from the start address of the input data indicated by the word **901-2**. The second component **910** includes data representative of the maximum number of bytes to be written to the shared memory **710** by the processing engine **706**. In the present example, each of the first component **908** and the second component **910** includes 16 bits. It is to be understood that the first component **908** and the second component **910** may have other bit-sizes.

Returning to FIG. **7**, the decoder logic **720** analyzes the first word of the auxiliary instruction to identify the task to be performed and its associated priority. The interface **704** is configured with knowledge of the hardware functionality of each of the sockets **718**. Based on this knowledge, the requested function/task, and the priority of the task, the interface **704** notifies the appropriate one of the sockets **718** to begin performing the requested task. In particular, the interface **704** informs the selected socket of the start address in the shared memory **710** for the input data to be processed. The

interface **704** processes each auxiliary instruction received from the APU **716** in a similar manner.

The interface **704** further includes memory arbitration logic **722** for arbitrating access to the memory controller **708** among the sockets **718**. That is, after a socket receives notification of a task to be performed, the socket requests access to the memory controller **708** (and ultimately the shared memory **710**) from the memory arbitration logic **722**. The interface **704** also includes processor arbitration logic **724** for arbitrating access to the processor **714** among the sockets **718**. For example, a socket may communicate an interrupt to the processor **714**. The interface **704** may also include a status register **726** that can be read by the processor **714**. The status register **726** may be used to inform the software running on the processor **714** whether a requested task has been completed, as well as only partially completed due to a number of possible reasons (e.g., limited memory space, unsupported features, and the like).

Each of the sockets **718** comprises a hardware block **730** and a wrapper **728**. The wrapper **728** provides a standard interface to the hardware block **730**. That is, each of the sockets **718** includes a standard interface to its respective hardware block. The wrapper **728** includes a data transfer state machine **750** to communicate with the interface **704** and a memory space **732** having a write-only register file **734**, a read-only register file **736**. The terms “write” and “read” are defined with respect to the interface **704**. That is, the interface **704** stores data to the write-only register file **734**, and reads data from the read-only register file **736**. Conversely, the hardware block **730** reads data from the write-only register file **734**, and writes data to the read-only register file **736**. Notably, the memory space **732** does not include read/write block memories, since actual input and output data is not communicated between the processor **714** and the interface **704**. Rather, communication between the interface **704** and the hardware block **730** is in the form of an instruction. The shared memory **710** is used to store both the input data and the resulting output data.

The register file memories **734** and **736** are used for writing and reading control signals. The write-only register file **734** is used to store flags and parameters that are required by the hardware block **730** (e.g., a status flag indicating the presence of input data). The read-only register file **736** is used to convey various flags and parameters computed by the hardware block **730** (e.g., a status flag indicating the presence of completed output data). The read-only register file **736** can also contain any information that the hardware block **730** would like to transmit to the processor block **702** (e.g., functional capabilities, estimated performance of specified tasks, etc.). An exemplary configuration for the memory space **732** of a socket is described immediately below with respect to FIG. **8**.

FIG. **8** is a functional block diagram depicting an exemplary embodiment of an interface between software running on the processor **714** and a socket **718-X** of the sockets **718** in the processing engine **706**. The memory space **732** includes one or more information registers **818**, a finish flag register **820**, and a start flag register **822**. The wrapper **728** for the socket **718-X** includes control logic **816**. The information registers **818** and the finish flag **820** form the read-only register file space, and the start flag **822** forms the write-only register file space.

The processor block **702** notifies the interface **704** of a requested task via the path **808**. The task request includes the start address in the shared memory **710** of the input data, the start address in the shared memory **710** for the output data, and the number of bytes to be read from and written to the

shared memory **710**. Various protocols may be used to perform the data transfer from the shared memory **710** (e.g., streaming data based on empty/full flags). One method is the use of the start flag register **822**. The interface **704** sets the start flag register **822** in response to the task request and communicates the address and byte count information to the control logic **816**. The control logic **816** detects the state of the start flag register **822** and signals the hardware block **730** to begin processing input data in the shared memory **710** at the start address of the input data. The hardware block **730** receives input data from the memory controller **708** through the interface **704** via the path **802**. The hardware block **730** sends data to be stored in the shared memory **710** to the interface **704** via the path **804**.

The hardware block **730** signals the control logic **816** after processing is complete and output data is stored in the shared memory **710**. In response, the control logic **816** sets the finish flag register **820**. Various protocols may be used to perform the data transfer to the shared memory **710** (e.g., streaming data based on empty/full flags, interrupt signals sent from the interface **720** to the processor **714**). One method is the use of the finish flag register **820**. In one embodiment, the interface **704** periodically polls the state of the finish flag register **820** and set the status register **726** to indicate that the task has been completed in response to the finish flag register **820** being set. The information registers **818** may be used to store data indicative of the capabilities of the hardware block **730**. For example, the information registers **818** may be configured to store a list of task(s) that the hardware block **730** is capable of performing, as well as a cost function related to how fast the hardware block **730** can perform the task(s).

While the foregoing describes exemplary embodiment(s) in accordance with one or more aspects of the present invention, other and further embodiment(s) in accordance with the one or more aspects of the present invention may be devised without departing from the scope thereof, which is determined by the claim(s) that follow and equivalents thereof. Claim(s) listing steps do not imply any order of the steps. Trademarks are the property of their respective owners.

The invention claimed is:

1. An apparatus for communication between a plurality of hardware blocks configured in an integrated circuit and a computation device external to the integrated circuit, comprising:

- a bus controller for receiving words from the computation device;
 - a first-in-first-out buffer (FIFO) in communication with the bus controller for storing the words;
 - a processing engine having respective memory spaces associated with the hardware blocks, the processing engine configured to store the words from the FIFO in the memory spaces;
 - an address decoder for decoding an address component of each of the words to obtain addresses of memory locations in the memory spaces;
 - a multiplexer having a control port coupled to the address decoder, input ports respectively coupled to the hardware blocks for receiving write-ready signals, and an output port coupled to a pop control terminal of the FIFO;
 - a strobe generator for providing strobe signals to the processing engine, the strobe signals configured to store the words in the respective memory locations; and
- wherein after a word is stored in the respective memory space associated with an addressed one of the hardware blocks, the addressed one of the hardware blocks asserts a respective write-ready signal to the multiplexer, in

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response to a control signal from the address decoder the multiplexer selects the respective write-ready signal for input to the pop control terminal, and a top word is popped from the FIFO.

2. The apparatus of claim 1, wherein each of the words further includes a control component, and wherein each of the hardware blocks is configured to receive the control component of each of the words.

3. The apparatus of claim 2, wherein for each word of the words the control component comprises data indicating that the word is valid.

4. The apparatus of claim 1, further comprising:

a direct memory access (DMA) controller coupled to the bus controller for controlling data transfers between the processing engine and the computation device.

5. The apparatus of claim 1, wherein the bus controller is configured to be a bus master of a system bus in the computation device.

6. The apparatus of claim 1, wherein the bus controller is further configured to receive read requests from the computation device, the apparatus further comprising:

a first multiplexer having first input ports respectively coupled to data output ports of the hardware blocks, a first control port coupled to the address decoder, and a first output port coupled to the bus controller; and

a second multiplexer having second input ports respectively coupled to strobe output ports of the hardware blocks, a second control port coupled to the address decoder, and a second output port coupled to the bus controller.

7. A method of communication between a plurality of hardware blocks configured in an integrated circuit and a computation device external to the integrated circuit, comprising:

receiving words from the computation device into a first-in-first-out buffer (FIFO) in the integrated circuit;

decoding an address component of a word at the top of the FIFO to select a memory location in a respective memory space associated with one of the hardware blocks;

storing a data component of the word to the selected memory location in the respective memory space associated with the one of the hardware blocks;

after the storing of the data component of the word in the respective memory space associated with the one of the hardware blocks, asserting a respective write-ready signal by the one of the hardware blocks;

selecting, in response to the decoded address component, the respective write-ready signal asserted by the one of the hardware blocks from a plurality of write-ready signals from the plurality of hardware blocks; and

popping a top word from the FIFO in response to the selected write-ready signal asserted by the one of the hardware blocks.

8. The method of claim 7, further comprising:

repeating the steps of decoding and storing for at least one additional word at the top of the FIFO.

9. The method of claim 7, wherein the data portion of the word is stored in the selected memory location by providing a strobe signal to the hardware block based on the selected memory location.

10. The method of claim 7, wherein the step of receiving the words comprises:

mastering a system bus in the computation device.

11. The method of claim 10, wherein the words are received using a direct memory access (DMA) process.

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12. The method of claim 7, further comprising: receiving read requests from the computation device; selecting a hardware block in response to the read request; and providing output data to the computation device from the hardware block.

13. A processing system, comprising:

a computation device having a processor and a memory coupled to a system bus; and

an integrated circuit configured to include an interface and a processing engine having respective memory spaces associated with a plurality of hardware blocks, the interface including:

a bus controller for receiving words from the system bus of the computation device;

a first-in-first-out buffer (FIFO) in communication with the bus controller for storing the words;

an address decoder for decoding an address component of each of the words to obtain addresses of memory locations in the memory space;

a multiplexer having a control port coupled to the address decoder, input ports respectively coupled to the hardware blocks for receiving write-ready signals, and an output port coupled to a pop control terminal of the FIFO; and

a strobe generator for providing a strobe signal to the processing engine, the strobe signal configured to store the words in the respective memory locations; and

wherein after a word is stored in the respective memory space associated with an addressed one of the hardware blocks, the addressed one of the hardware blocks asserts a respective write-ready signal to the multiplexer, in response to a control signal from the address decoder the multiplexer selects the respective write-ready signal for input to the pop control terminal, and a top word is popped from the FIFO.

14. The system of claim 13, wherein each of the words further includes a control component, and wherein each of the hardware blocks is configured to receive the control component of each of the words.

15. The system of claim 14, wherein for each word of the words the control component comprises data indicating that the word is valid.

16. The system of claim 13, wherein the interface further comprises:

a direct memory access (DMA) controller coupled to the bus controller for controlling data transfers between the processing engine and the computation device.

17. The system of claim 13, wherein the bus controller is configured to be a bus master of the system bus in the computation device.

18. The system of claim 13, wherein the bus controller is further configured to receive read requests from the computation device, the apparatus further comprising:

a first multiplexer having first input ports respectively coupled to data output ports of the hardware blocks, a first control port coupled to the address decoder, and a first output port coupled to the bus controller; and

a second multiplexer having second input ports respectively coupled to strobe output ports of the hardware blocks, a second control port coupled to the address decoder, and a second output port coupled to the bus controller.